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MECHANISM-DEPENDENT FRACTAL CHARACTER OF FRACTURE SURFACES IN HIGH STRENGTH AND TOUGHNESS ASTM A723 STEELS

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The fractal character of fracture surfaces of thick-walled pressure vessels produced in the final fast fracture that terminates low cycle fatigue tests is compared with that of fracture surfaces produced in Charpy impact tests in samples of the same high strength and toughness steel (ASTM A723) alloy. Slit island analysis yielded fractal dimensions near 1.25 for the Charpy specimens, which is typical of high strength steel alloys previously studied; however, extremely high fractal dimensions near 1.40 were determined for the low cycle fatigue specimens. The distributions of island and lake areas and of island and lake perimeters on random sections exhibit hyperbolic distributions analogous to those found for geographic islands and lakes.

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INTRODUCTION

The fractal character of fracture surfaces produced by Charpy impact and by the final fast fracture of thick-walled pressure vessels during low cycle fatigue testing in high strength and toughness ASTM A723 (modified AISI 4340 with 0.2 percent vanadium) steels has been determined.

Substantial differences were observed in the qualitative appearance and in the fractal character of the fracture surfaces produced by the two mechanisms. The Charpy specimens were typical of high toughness steel fracture surfaces (refs 1-5) and had fractal dimension approximately 1.25, while the low cycle fatigue specimen exhibited an extremely high fractal dimension near 1.40. Since the character of the low cycle fatigue specimen fracture was atypical of fracture surfaces in high toughness steels previously studied, a thorough study of its structure was undertaken.

We follow the usual convention of giving the fractal dimension as that determined for islands and/or lakes on sections through the fracture surface. Thus, according to Mandelbrot's rule for sections, the actual fracture surface fractal dimensions are 1.0 greater than the fractal dimensions reported here.

EXPERIMENTAL

Charpy Specimen

Charpy specimens were standard notched 3/8 inch ASTM A723 bars with a nominal strength of 160 Ksi and hardness of 38 Rc. Fracture surfaces were coated with electroless nickel prior to grinding on a metallurgical polishing wheel to obtain the island and lake configuration. Perimeter and area measurements were obtained with the JAVA™ image analysis system (ref 6).

Low Cycle Fatigue Specimen

The low cycle fatigue specimen fracture surface was produced in a 10-cm inner diameter thick-walled cylinder subjected to hydraulic pressure cycling, which culminates in a final fast fracture when the fatigue crack depth exceeds the critical crack length (refs 7,8).

A large section (2 inches by 5 inches) of the fracture surface was selected for analysis. Electroless coating of the surface to protect fine detail during grinding was unnecessary because of the low magnification used for the large islands and lakes on this specimen. However, lake regions were filled with paint to enhance contrast. The images were recorded with a video camera and analyzed with the JAVA™ system (ref 6).

DATA ANALYSIS

The primary analytical technique employed in these experiments was the slit island method of Mandelbrot, Passoja, and Paullay (ref 1). Island data were accumulated, ignoring lakes within islands, and lake data were accumulated, ignoring islands within lakes.

Conventional slit island analysis was performed on the islands produced by sectioning the Charpy bars.

The low cycle fatigue specimen was more extensively studied. Conventional slit island analysis was supplemented by separate analyses of island and lake data on individual sections. The distributions of island and lake areas on individual sections and of the combined data were also fit to the Korcak empirical law (i.e., a hyperbolic distribution function) as suggested in the discussion of diameter-number relations by Mandelbrot (ref 9). Curve fitting and computation employed MATLAB™ software (ref 10).

RESULTS

Slit Island Analysis

1. Charpy impact fracture. The log-log perimeter-area data in Figure 1 are typical of slit island results obtained from Charpy fractures in tempered martensite for ASTM A723 steels. The $\log_{10}$ (perimeter) values shown comprise about seventy islands and are linear in $\log_{10}$ (area) over about four orders of magnitude in the area (from about 10^{-5} to 10^{-2} mm^2); the fractal dimension is determined to be 1.25. Values of the fractal dimension measured for Charpy impact fractures in A723 steels ranged between about 1.20 and 1.30.

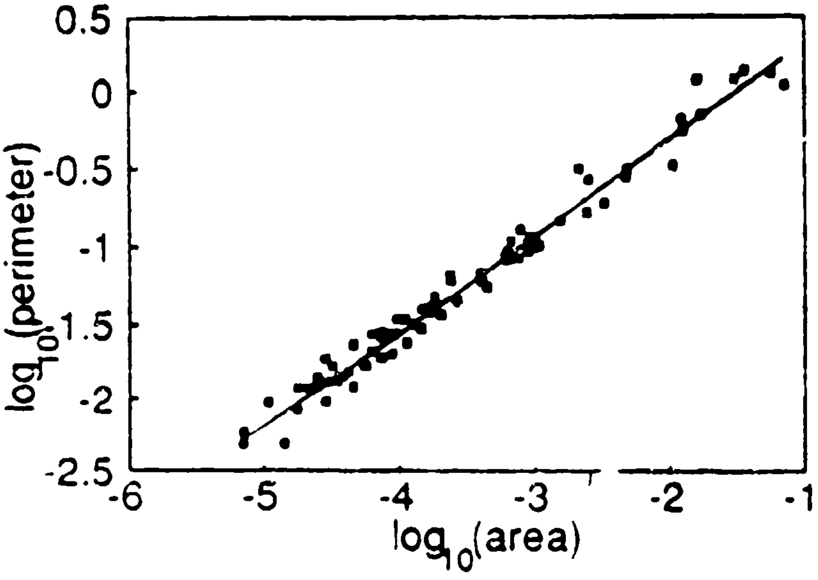

Figure 1. $\log_{10}$ (perimeter) versus $\log_{10}$ (area) for a typical Charpy fracture surface. One unit of perimeter is approximately 0.1 cm and one unit of area is approximately 0.01 cm^2. The least-squares fit line yields D = 1.25.

2. Low cycle fatigue specimen fracture. Perimeter-area plots were obtained for a sequence of sections through the low cycle fatigue specimen fracture surface. Each section comprised about two hundred islands or lakes. Areas varied from about 0.5 10^{-3} to 10^3 mm^2.

a. Island sections. The initial sections, which exhibited (essentially) only islands, and intermediate depth sections, which exhibited comparable numbers of islands and lakes, provided data for eleven separate island-only perimeter-area analyses. The data were strikingly consistent. Fractal dimension determinations on the individual sections ranged from 1.37 to 1.41; the combined data yielded 1.40. There was a trend toward lower values at deeper sections. Figure 2 shows the perimeter-area (in arbitrary units) data for the combined island data and for a typical section.

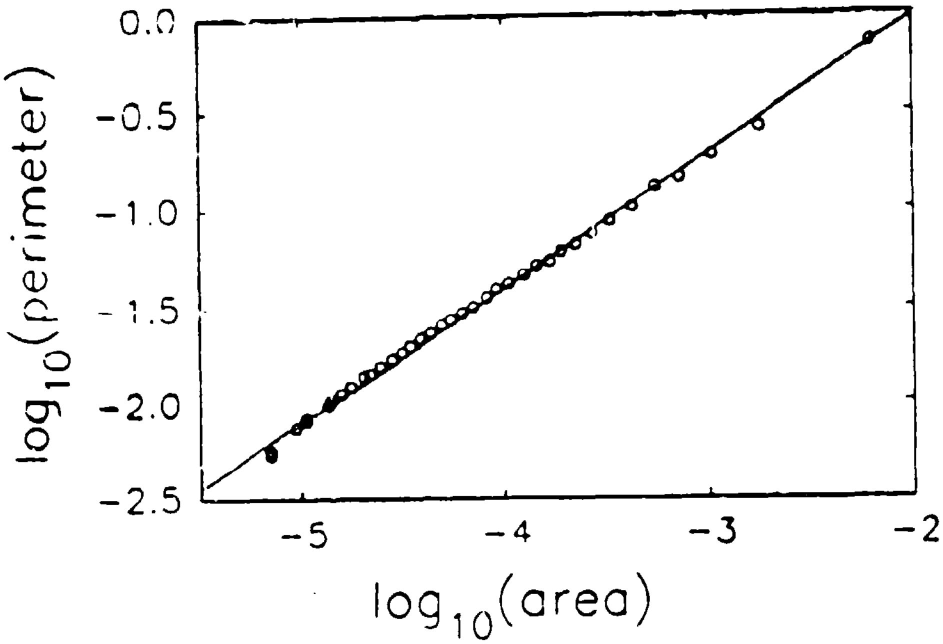

Figure 2. Sorted and averaged $\log_{10}$ (perimeter) versus $\log_{10}$ (area) for all island sections in low cycle fatigue fracture surface. The islands are sorted in order of increasing area and arranged into sets of 50 islands. Each point represents the average value for a set of 50 islands (e.g., the nth point represents the average values for islands ($50n-49$) through $50n$ in the sorted list). The least-squares fit line yields D = 1.395 ± 0.004.

b. Lake sections. The deeper sections provided data for seven separate lake perimeter-area analyses. The data were remarkably consistent among themselves and with the results of the island analyses. Fractal dimension determinations on the individual sections ranged from 1.36 to 1.39; the combined data yielded 1.37. Figure 3 exhibits the perimeter-area dependence of the combined lake data.

__Area-Number Relations__

Hyperbolic distributions and fractal structures are closely related. For example, in the theory of self-ordered criticality they reflect absence of intrinsic time and spatial scales, respectively. Mandelbrot's discussion (ref 9) of diameter-number relations for geographic islands defined by sea level, suggested that islands produced by sections through fractal surfaces should exhibit hyperbolic distributions. (Mandelbrot credits J. Korcak with the discovery of the existence of such distributions and refers to them as Korcak distributions.)

The generalized Korcak law, as formulated by Mandelbrot (ref 9), relates the hyperbolic area-number relation and the fractal dimension of the surface as

$$N_r(A > a) = F\, a^{D/2}$$

where $N_r(A > a)$ is the total number of islands of area greater than a, and D is the surface fractal dimension. Mandelbrot (ref 9) also asserts that the fractal dimension D, governing the hyperbolic distribution, can exceed the coastline fractal dimension D_c as a result of "fragmentation."

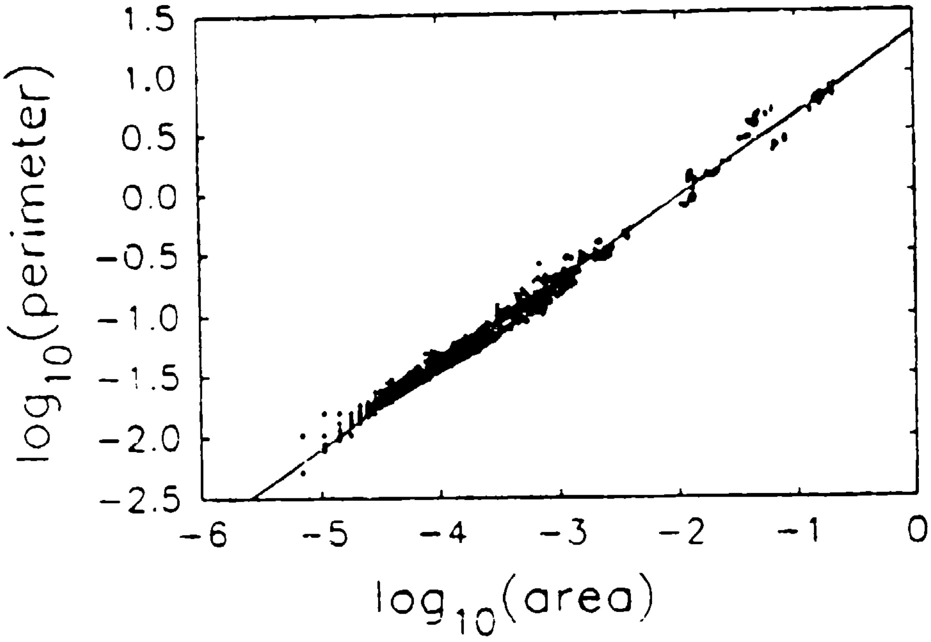

Figure 3. $\log_{10}$ (perimeter) versus $\log_{10}$ (area) for all lake sections in low cycle fatigue fracture surface. One unit of perimeter is approximately 2.4 cm and one unit of area is approximately 5.7 cm^2. The least-squares fit line yields $D = 1.372 \pm 0.0041$.

1. Island sections. The number-area data accumulated for all the islands in the low cycle fatigue fracture surface are shown in Figure 4. The data are consistent with a hyperbolic distribution over three orders of magnitude in the area. Least-squares fitting yields $D \approx 1.54$, which is substantially greater than the coastline fractal dimension ($D_c = 1.40$) and would seem to imply a substantial fragmentation contribution to D. Furthermore, analyses of the hyperbolic distribution of island areas for individual sections also gave D values greater than D_c. The deviations of the deduced D values were within $\pm$ 15 percent of 1.54 over the eleven island sections.

A smaller D would be obtained for the island number-area data if one invoked a smaller "outer cutoff" on the distribution, but the data are essentially linear over the three orders of magnitude in the area over which the parameters were fit.

2. Lake sections. The lake sections were consistent with a hyperbolic distribution over about one and a half orders of magnitude; however, for the lake sections, the deduced dimension ($D \approx 1.40$) is in close accord with the coastline fractal dimension.

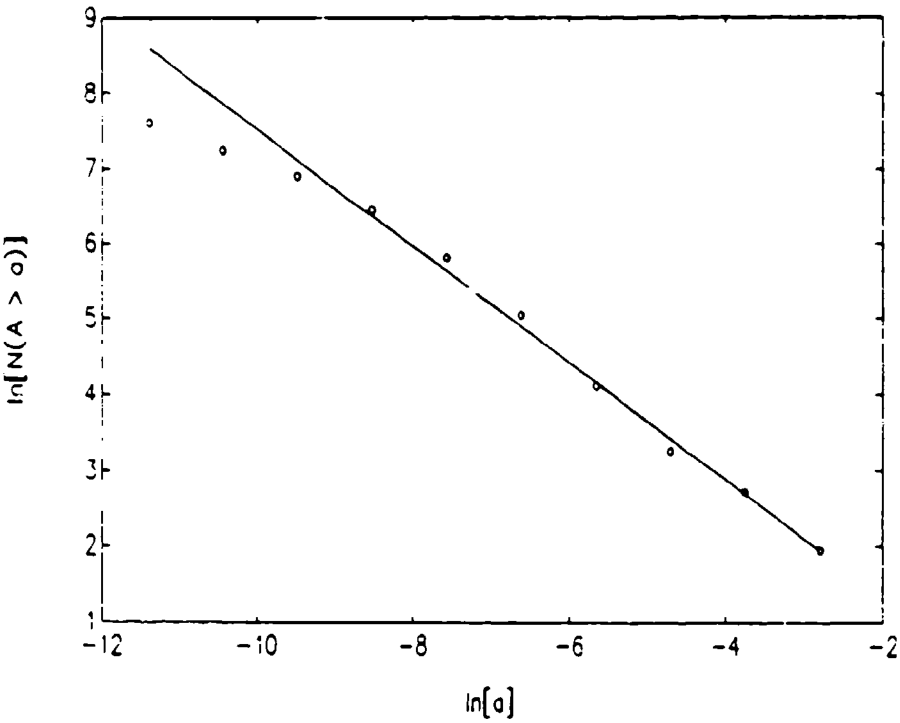

Figure 4. Korcak plot for island sections. The least-squares fit line through the linear portion (points 3 to 10) yields D = 1.54 ± 0.06.

DISCUSSION

Perimeter-area analysis was applied to fracture surfaces produced in Charpy impact and low cycle fatigue tests in high strength and toughness ASTM A723 (modified AISI 4340 with 0.2 percent vanadium) steels. The fractal dimension of the Charpy impact fracture surfaces was determined to be approximately 1.25, which is consistent with the results of other fractal studies of fracture in high strength steels (refs 1-5). However, the fractal dimension was determined to be approximately 1.39 for low cycle fatigue fracture, an extremely high value for fracture in a high strength and toughness steel alloy.

The major difference in the two experiments is the scale over which the fractures were generated. The Charpy fracture surfaces were studied under a microscope and island areas ranged from about 10^{-5} to abut 10^{-2} mm^2. The low cycle fatigue specimen fracture surfaces studied were about 10 cm across, and the island area ranged from about 0.5 10^{-3} to about 10^3 mm^2. There was approximately one order of magnitude overlap in the ranges of area or perimeter.

The region studied in the low cycle fatigue specimen fracture was more than 10 mm from the initiation of fracture, while the Charpy fracture surface studied was within about 0.3 mm from the point of initiation of the fracture.

The rate of crack growth in the Charpy test and in the final fast fracture of the low cycle fatigue specimen are presumed to be comparable.

Since the higher fractal dimension is associated with a higher degree of complexity, a tentative conclusion from these data is that the complexity of the fracture surfaces increases with volume available for fracture.

The distributions of areas and perimeters of islands and lakes produced by sectioning the low cycle fatigue specimen fracture surface were hyperbolic in accord with the principle, the Korcak law, which Mandelbrot advanced to describe the distribution of geographic islands.

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